

WOPPER, Version 1.5:
 A Monte Carlo Event Generator for
 $e^+e^- \rightarrow (W^+W^-) \rightarrow 4f + n\gamma$
 at LEP2 and beyond*

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Abstract

We describe the new version of the Monte Carlo event generator WOPPER for four fermion production through W -pairs including resummed leading logarithmic QED radiative corrections. Among the new features included are singly resonant background diagrams and anomalous triple gauge boson couplings.

Program Summary:

- **Title of program:** WOPPER, Version 1.5 (May 1996)
- **Program obtainable from:** crunch.ikp.physik.th-darmstadt.de in the directory /pub/ohl/wopper (using anonymous Internet ftp)
- **Licensing provisions:** none
- **Programming language used:** FORTRAN-77
- **Computer/Operating System:** Any with a FORTRAN-77 environment
- **Number of program lines in distributed program, including test data, etc.:** ≈ 10000 (Including comments)
- **Keywords:** radiative corrections, W pair production, W decays, multi-photon radiation, anomalous couplings.

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- **Nature of physical problem:** Higher order leading logarithmic QED radiative corrections to W pair production and decay at high energy e^+e^- colliders, including finite width of the W 's and anomalous trilinear gauge boson couplings.
- **Method of solution:** Monte Carlo event generation.
- **Restrictions on the complexity of the problem:** The matrix elements for the hard subprocess contain only the doubly and singly resonant contributions constituting the so-called "CC11" diagrams, in the Born approximation. The hadronization of final state quarks is handled by external programs. Interfaces to the most popular QCD Monte Carlos are provided.
- **Typical running time:** The time needed per unweighted event depends on the beam energy, cuts and CPU. The test run (10000 unweighted parton level events at LEP2 energies) takes approximately 420 CPU seconds on an aging 486DX2/66 PC running Linux 2- ϵ . On contemporary personal computers, the 42 ms/event will be reduced to 5 ms/event and work stations will need less than 1 ms/event. The CPU time per event increases mildly with the beam energy.

1 Introduction

The spectacular success of the high energy electron positron colliders LEP at CERN and SLC at SLAC has confirmed the predictions of the Standard Model (SM) for the interactions between the gauge bosons and the fermions even at the level of electroweak radiative corrections. The high precision of the experimental data allows to put limits on parameters of yet unobserved particles like the Higgs boson through the appearance of these particles in weak loop corrections. On the other hand, the non-Abelian structure of the gauge sector of the SM predicts couplings between the electroweak gauge bosons which have not been tested directly. The forthcoming upgrade of LEP [1, 2] to LEP2 [3, 4] with a center of mass energy of up to $\sqrt{s} \approx 200$ GeV and a future 0.5–1.5 TeV e^+e^- linear collider [5] (NLC, for short) will in particular make the trilinear $WW\gamma$ and WWZ couplings directly observable through their contribution to the production of W pairs.

The main task of LEP2 will be a precise determination of the mass and the width of the W and the production cross section in the threshold region [6]. At NLC, a measurement of the total cross section, the W angular distributions and in particular of their longitudinal polarization component will give a handle on possible anomalous couplings among the electroweak bosons induced by new physics beyond the SM [7, 8], and in turn reveal an insight into the mechanism of electroweak symmetry breaking.

However, possible new physics is already severely constrained by present LEP and SLC data, and the effects to be expected at NLC (even more so at LEP2) are small. In order to extract these small effects, one has to have a precise knowledge of the radiative corrections within the SM.

The electroweak radiative corrections to the production of on-shell W 's to one-loop order are by now well established [9, 10]. The influence of the finite width of the W 's has been investigated in [11, 12]. Also, the higher order QED corrections have been calculated in the leading log approximation (LLA) and their importance has been emphasized in ref. [13]. An exhaustive overview of the standard model predictions has been provided in [14] and [4].

Unfortunately, the experimental reconstruction of the W 's and the determination of their polarization is complicated by the fact that they may decay either into leptons with an escaping neutrino, or into hadrons, where the jet energies may be poorly known due to undetected particles. In addition, the radiative corrections due to emission of photons produce a systematic shift of the effective center of mass energy towards smaller values. Such effects may best be studied with the help of a Monte Carlo event generator.

Although quite a few semianalytical calculations of the corrections mentioned above have been available for some time, version 1.0 of WOPPER [15] had been the first publicly available and complete Monte Carlo event generator. In the meantime, many new programs have been released [4].

This paper describes version 1.5 of the Monte Carlo event generator WOPPER. It is based on the lowest order cross section for the process $e^+e^- \rightarrow (W^+W^-) \rightarrow 4f$ and focusses on QED radiative corrections in the LLA resummed to all orders in α and the effects of finite width of the W 's. The four-momenta of the exclusive hard photons are generated explicitly and treated with full kinematics. The W decays into fermions are implemented at the parton level, including leading QCD corrections to the W branching fractions.

This write-up is organized as follows: In section 2 we outline the physics underlying the algorithms implemented in **WOPPER**. The actual implementation is described in section 3. The parameters controlling the execution of **WOPPER** are discussed in detail in section 4 and the **FORTRAN-77** interface is presented in section 5. Distribution notes, a listing of all external symbols and the output of a test run can be found in the appendices.

2 Theoretical Background and General Features

2.1 QED corrections at very high energies

In the structure function formalism [16, 17, 18] the expression for the radiatively corrected cross section reads

$$\sigma(s) = \int_0^1 dx_+ dx_- D(x_+, Q^2) D(x_-, Q^2) \hat{\sigma}(x_+ x_- s), \quad (1)$$

where $\hat{\sigma}$ is the Born level cross section of the hard process, $D(x, Q^2)$ are the structure functions for initial state radiation, and Q^2 is the factorization scale.

The structure functions D sum the numerically most important leading logarithmic contributions

$$\frac{\alpha}{\pi} \log \left(\frac{s}{m_e^2} \right) \approx 6\% \quad (\text{at LEP2 and NLC energies}) \quad (2)$$

to the electromagnetic radiative corrections to all orders. They satisfy the QED evolution equation [16]

$$Q^2 \frac{\partial}{\partial Q^2} D(x, Q^2) = \frac{\alpha}{2\pi} \int_x^1 \frac{dz}{z} [P_{ee}(z)]_+ D\left(\frac{x}{z}, Q^2\right) \quad (3)$$

$$P_{ee}(z) = \frac{1+z^2}{1-z} \quad (4)$$

with initial condition

$$D(x, m_e^2) = \delta(1-x). \quad (5)$$

The solution to eq. (3) automatically includes the very important exponentiation of the soft photon contributions to the radiative corrections.

An explicitly regularized version of (3) used in the Monte Carlo implementation is given by

$$\begin{aligned} Q^2 \frac{\partial}{\partial Q^2} D(x, Q^2) &= \frac{\alpha}{2\pi} \int_x^{1-\epsilon} \frac{dz}{z} P_{ee}(z) D\left(\frac{x}{z}, Q^2\right) \\ &\quad - \frac{\alpha}{2\pi} \left[\int_0^{1-\epsilon} dz P_{ee}(z) \right] D(x, Q^2). \end{aligned} \quad (6)$$

It is crucial to note that the characteristics of the generated event sample do not depend on ϵ , if it is chosen well below the experimental threshold for the

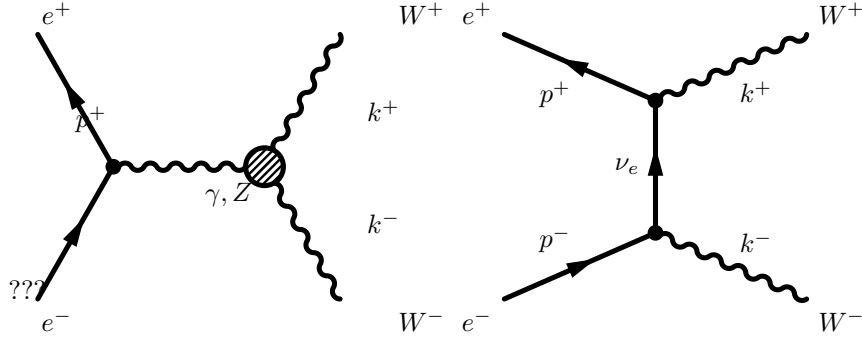


Figure 1: The Feynman diagrams contributing to the on-shell production $e^+e^- \rightarrow W^+W^-$.

detection of soft photons. Theoretically, the cross sections will remain positive for *all* values of ϵ , but limited storage for ultra soft photons and limited floating point range impose a lower limit.

The radiatively corrected cross section (1) is implemented in a Monte Carlo event generator by solving the integro-differential equation (6) by iteration and taking into account the energy loss in the hard cross section. It is very similar to algorithms for quark fragmentation in QCD [19]. As a by-product of the branching algorithm, the four-momenta of the radiated photons are generated explicitly.

The initial state branching algorithm has already been used in the Monte Carlo generator KRONOS [20] and an improved version in the generator UNIBAB [21], where the implementation has been described in detail.

The momenta of the electron and positron after initial state branching are then used as the input momenta for the subgenerator of the hard subprocess described below.

2.2 Born Cross Section

In the general case, there are many Feynman diagrams contributing to the process $e^+e^- \rightarrow 4$ fermions at high energies, even if one requires that the quantum numbers of the final state fermions be consistent with W pair production [4]. However, the contribution of the individual Feynman diagrams may be easily estimated by counting the number of resonant propagators, where an intermediate vector boson may come close to its mass shell. Using this naive estimate, one finds that the contribution of these ‘background diagrams’ is suppressed by a factor $\Gamma_W/M_W \sim 2.5\%$ for each non-resonant boson propagator, and may be reduced further by appropriate cuts on the invariant masses of the reconstructed W ’s. In fact, a full calculation [22] finds that this estimate is numerically justified for LEP2 energies, unless electrons are in the final state and no invariant mass cuts are applied.

In the current version 1.5 of WOPPER, we have taken into account the doubly and singly resonant Feynman diagrams shown in figures 2 and 3, also known as the “CC11” diagrams [4]. Note that the combination of the fermions 1 and 2 has quantum numbers consistent with a W^+ , while the combination of the fermions 3 and 4 has quantum numbers consistent with a W^- , even for the singly resonant diagrams. We will refer to these pairs as “pseudo- W ’s” below.

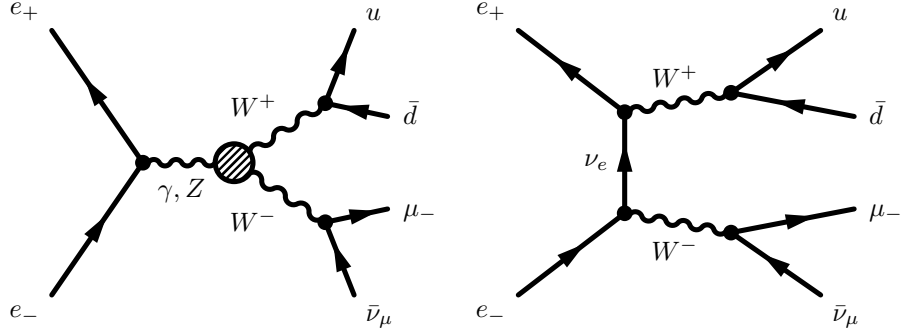


Figure 2: The “CC03” subset of Feynman diagrams contributing to four fermion production $e^+e^- \rightarrow 4f$.

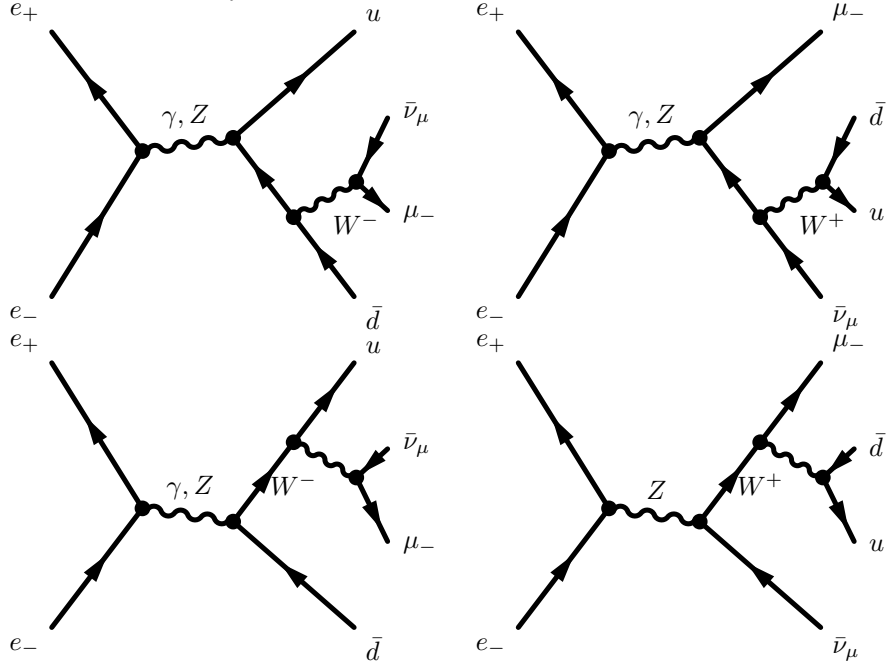


Figure 3: The “CC11” subset of Feynman diagrams contributing to four fermion production $e^+e^- \rightarrow q\bar{q}'q''\bar{q}'''$. For $q\bar{q}'\ell\nu_\ell$ and $\ell^-\bar{\nu}_\ell\ell^+\nu_\ell$ final states only 10 and 9 diagrams contribute, respectively, because of the uncharged neutrinos in the intermediate states.

In the calculation of the Born amplitudes, we use an energy dependent width for both the W and Z propagators, that is given by the contributions of the light fermions to the vector boson self energies:

$$\text{Im } \Sigma_W(k^2) \equiv \sqrt{k^2} \cdot \Gamma_W(k^2) \approx \frac{k^2}{M_W^2} M_W \Gamma_W, \quad \text{Re } \Sigma_W(k^2) \approx 0 \quad (7)$$

and similarly for Z 's.

It can easily be seen that, after integrating the modulus squared of the Born amplitudes over the decay angles of the pseudo W 's, one obtains the same resonance formula for the total cross section for production of the pseudo W

pairs as in the well known doubly resonant case [11, 23, 24], for each combination of final state fermions $f_1 \bar{f}_2 f_3 \bar{f}_4$:

$$\sigma(12, 34) = \int ds_+ ds_- \frac{\sqrt{s_+} \Gamma_{W \rightarrow 12}(s_+)}{\pi D(s_+)} \frac{\sqrt{s_-} \Gamma_{W \rightarrow 34}(s_-)}{\pi D(s_-)} \sigma_{\text{off}}(s; s_+, s_-; 12, 34) \quad (8)$$

Here $\sigma_{\text{off}}(s; s_+, s_-)$ denotes the off-shell cross section for the production of two pseudo- W 's, and $\Gamma_W(s_\pm)$ is the effective decay width of a virtual W into light fermions according to eq. (7). The resonance factors are Breit-Wigner functions with energy-dependent width:

$$\frac{1}{D(s_\pm)} = \frac{1}{(s_\pm - M_W^2)^2 + s_\pm \Gamma_W^2(s_\pm)} \quad (9)$$

Note that equation (8) also holds for the total cross section, after summation of over the decay channels of the pseudo W 's:

$$\sigma = \int ds_+ ds_- \frac{\sqrt{s_+} \Gamma_W(s_+)}{\pi D(s_+)} \frac{\sqrt{s_-} \Gamma_W(s_-)}{\pi D(s_-)} \sigma_{\text{off}}(s; s_+, s_-) \quad (10)$$

For the actual implementation it is useful to apply the mappings ($\gamma \equiv \Gamma_W/M_W$)

$$\xi_\pm = \arctan \left(\frac{(1 + \gamma^2)s_\pm - M_W^2}{\gamma M_W^2} \right) \quad (11)$$

to eq. (10) in order to get a smooth integrand suitable for a Monte Carlo rejection algorithm:

$$\begin{aligned} \sigma &= \int d\xi_+ d\xi_- \frac{1}{\pi} \frac{s_+}{M_W^2} \frac{1}{\pi} \frac{s_-}{M_W^2} \sigma_{\text{off}}(s; s_+, s_-) \Big|_{s_\pm = M_W^2 \cdot (1 + \gamma \tan \xi_\pm) / (1 + \gamma^2)} \\ &\equiv \int d\xi_+ d\xi_- \tilde{\sigma}(s; \xi_+, \xi_-) \end{aligned} \quad (12)$$

2.3 Triple gauge bosons couplings

In order to model the triple gauge boson vertices $WW\gamma$ and WWZ including possible deviations from the Standard Model (“anomalous couplings”), we use an effective Lagrangian as given by Hagiwara et al. [8]:¹

$$\begin{aligned} \mathcal{L}_{WWV}/g_{WWV} &= ig_1^V (W_{\mu\nu}^\dagger W^\mu - W_\mu^\dagger W_{\nu}^\mu) V^\nu + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} \\ &\quad + \frac{i\lambda_V}{m_W^2} W_{\lambda\mu}^\dagger W^\mu{}_\nu V^{\nu\lambda} - g_4^V W_\mu^\dagger W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\ &\quad + g_5^V \epsilon^{\mu\nu\lambda\sigma} \left(W_\mu^\dagger \overleftrightarrow{\partial}_\lambda W_\nu \right) V_\sigma + i\tilde{\kappa}_V W_\mu^\dagger W_\nu \tilde{V}^{\mu\nu} \\ &\quad + \frac{i\tilde{\lambda}_V}{m_W^2} W_{\lambda\mu}^\dagger W^\mu{}_\nu \tilde{V}^{\nu\lambda} \end{aligned} \quad (13)$$

Here V^μ stands for either the photon or the Z field, W^μ is the W^- field, $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$, $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, and $\tilde{V}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\lambda\sigma} V^{\lambda\sigma}$.

¹Here we use the conventions of Itzykson and Zuber with $\epsilon^{0123} = +1$.

These seven operators exhaust all possible Lorentz structures when we neglect the scalar components of the vector bosons,

$$\partial_\mu V^\mu = 0, \quad \partial_\mu W^\mu = 0. \quad (14)$$

which is allowed if we couple the bosons to (almost) massless external fermions.

In accordance with Hagiwara et al. [8] we choose

$$g_{WW\gamma} = -e, \quad g_{WWZ} = -e \cot \theta_W. \quad (15)$$

In the Standard Model at tree level we then have:

$$g_1^\gamma = g_1^Z = \kappa_\gamma = \kappa_Z = 1, \quad \text{all others couplings} = 0 \quad (16)$$

We demand P and C conservation separately for the $WW\gamma$ vertex, thus we have to set

$$g_4^\gamma = g_5^\gamma = \tilde{\kappa}_\gamma = \tilde{\lambda}_\gamma = 0. \quad (17)$$

Electromagnetic gauge invariance requires that g_1^γ is related to the charge of the W,

$$g_1^\gamma = 1, \quad (18)$$

so that we have only two free parameters ($\kappa_\gamma, \lambda_\gamma$) for the $WW\gamma$ vertex, while there are seven for the WWZ vertex.

For convenience, the anomalous couplings can also be specified in another popular parameterization ($\delta_Z, x_\gamma, x_Z, y_\gamma, y_Z, z_Z$). The translation formulae are presented in section 4.2 below.

2.4 Coulomb singularity

Another class of universal corrections, which is important near threshold, is the so-called Coulomb singularity. We implement the correction [25]

$$\sigma_{\text{Coulomb}} = \sigma_{\text{Born}} \frac{\alpha\pi}{2\beta} \left(1 - \frac{2}{\pi} \arctan \left(\frac{|\beta_M + \Delta|^2 - \beta^2}{2\beta \text{Im} \beta_M} \right) \right) \quad (19)$$

to the off shell total cross section (10). Stricly speaking, this correction should only be applied to the subset of doubly resonant diagrams. However, the Coulomb correction is only large for the W 's close to their mass shell where the singly resonant diagrams are suppressed, and thus we apply it as a universal correction factor.

2.5 Decays of the pseudo W 's

In the case of the doubly resonant diagrams, the relative probabilities of the final state fermions are simply given by the branching fractions of the W 's. This remains true even after taking into account the inclusive QCD corrections to the W decays to quarks to first order in α_S , because of the factorization of the amplitude into W production and decay. Neglecting fermion masses, one has:

$$\Gamma(W \rightarrow q\bar{q}') = N_C \left(1 + \frac{\alpha_S}{\pi} \right) \Gamma(W \rightarrow \ell\nu_\ell) \quad (20)$$

However, in the case of the inclusion of the singly and doubly resonant diagrams, it is not clear how to take the QCD corrections into account, since no full calculation is as yet available. Neglecting QCD corrections to final states with quarks is clearly unacceptable, and simply multiplying the contribution of the doubly resonant diagrams with the QCD correction factor spoils the gauge cancellations between singly and doubly resonant diagrams. Therefore, we have taken the approach to implement the QCD corrections in (8) by using an “effective number of colors”

$$N_C^{\text{eff}} = N_C \left(1 + \frac{\alpha_S}{\pi} \right) ,$$

which we refer to as the “naive QCD corrections”.

The final state fermions of the decay $W \rightarrow f\bar{f}'$ are therefore chosen with a probability according to the cross sections obtained from (8), with the naive QCD corrections applied as described above. The branching fractions for hadronic decays into u , d , c , s , and b quarks are given by the corresponding CKM matrix elements, while decays into t quarks are assumed to be kinematically forbidden because of $|m_t - M_W| \gg \Gamma_W$. Currently, the fermion masses are only taken into account kinematically and not in the matrix elements.

The angular distributions of the pseudo W ’s and of the decay fermions is generated by a standard mapping and rejection algorithm from the differential cross section $d\sigma(s; s_+, s_-; \theta; 12, 34)/d\Omega$ and from the modulus squared matrix element, respectively.

2.6 Hadronization

If one or both of the W ’s have decayed into quarks, they can optionally be hadronized using either the LUND string model [26], the HERWIG cluster model [27] or the ARIADNE [28] color dipole model. In the present version it is not possible² to study color-rearrangement effects in purely hadronic decays. Both W decays are handled separately.

The hadronization model can be switched at run time with the parameter `qcdmc`, which takes the values 0, 1, 2 and 3. These correspond to no parton level, JETSET [26], HERWIG [27] and ARIADNE [28] respectively.

3 Implementation of WOPPER 1.5

Like almost all Monte Carlo event generators, WOPPER is divided into three parts: initialization, event generation, and termination. These are described in this section. For ease of use, WOPPER comes with two application interfaces, so that a direct call to the lower level parts in this section will never be necessary. These interfaces will be explained in section 5.

3.1 Initialization

The initializations in WOPPER are used for computing the value of variables that will be used frequently during event generation. Examples are the calculation of electroweak couplings, the maximum of the off-shell Born cross section and other

²Unless one makes the necessary changes to the WOPPER sources in routines `wlund()`, `whwig()` and `wwaria()`.

internal steering parameters from the input parameters. This is accomplished by a call to the subroutine `wwinit` after setting the Monte Carlo parameters. Since `WOPPER` does not yet include weak corrections, most of the initializations performed are quite trivial.

Finally, a standard `/hepevt/` initialization record [2] is written, which may be used by the analysis program.

3.2 Event Generation

The routine `wwgen` produces an event on every call. The four momenta of all generated particles as well as supplemental information is written to a standard `/hepevt/` event record, where it can be read by user supplied analyzers. See section 3.4 below for details on `WOPPER`'s extensive use of `/hepevt/`.

The first step is the generation of the initial state radiation by the branching routine `wwbini` using the algorithm of section 2.1 and of the virtual masses of the pseudo W 's occurring in the intermediate state. According to the cross section (12), the rejection weight is calculated from the ratio of the actual off-shell cross section to the maximum determined in the initialization step, and the event is accepted with a probability according to this weight.

After the effective center of mass energy and the pseudo W masses have been fixed, the quantum numbers of the event (helicity of incoming fermions and type of final state particles) are determined with probabilities proportional to their relative cross sections. The angular distribution and four-momenta of the pseudo W 's are generated in `wwgww` and `wwgppr`, respectively. Finally, the decay of the intermediate W 's into the final state fermions is accomplished in the subroutine `wgdec`.

3.3 Termination

The cross section for the generated events is obtained in the subroutine `wwclos` from the standard formula

$$\sigma_{tot}(s) = \max_{s'; \xi_+, \xi_-} \{ \tilde{\sigma}(s'; \xi_+, \xi_-) \} \cdot \frac{\# \text{ of successful trials}}{\text{total } \# \text{ of trials}} \quad (21)$$

where $\tilde{\sigma}$ is the off-shell cross section from eq. (12). s' varies between 0 and s , and ξ_{\pm} in the range allowed by the specified cuts. The corresponding statistical error from the Monte Carlo integration is given by

$$\Delta\sigma_{tot}(s) = \max_{s'; \xi_+, \xi_-} \{ \tilde{\sigma}(s'; \xi_+, \xi_-) \} \cdot \sqrt{\frac{(\text{total } \# \text{ of trials} - \# \text{ of successful trials}) \cdot \# \text{ of successful trials}}{(\text{total } \# \text{ of trials})^3}} \quad (22)$$

The cross section and the error on the cross section are placed into `/hepevt/`, where they may be read by the user-supplied analyzer.

3.4 Additional information in `/hepevt/`

Because `WOPPER` uses the standard `/hepevt/` event record internally, not only stable particles with `isthep(i) = 1` will be present. Adapting the conventions of the `HERWIG` Monte Carlo [27], we use the following status codes

- 101: e^- beam (positive z -direction),
- 102: e^+ beam (negative z -direction),
- 103: center of mass system of the collider,
- 110: e^+e^- hard scattering center of mass system,
- 111: e^- before hard scattering,
- 112: e^+ before hard scattering,
- 113: virtual W^- after hard scattering,
- 114: virtual W^+ after hard scattering.

However, these entries have *no* physical significance and should *never* be used in any analysis (an exception to this rule are the beam particles 101 and 102, which are convenient for defining the reference frame and are used e.g. by the analyzer **hepawk** [29] for this purpose). Only the particles with status code 1 belong to the final state as predicted by **WOPPER**.

If no hadronization Monte Carlo is active, final state quarks will be entered as “stable” particles with status code 1.

4 Parameters

The parameters controlling **WOPPER** version 1.5 are summarized in tables 1, 2 and 3. They will be described in the following subsections.

4.1 Electroweak Parameters

Since the present version of **WOPPER** does not include an electroweak library, the electroweak parameters, namely the masses of the electroweak bosons (**mass1w**, **mass1z**), their widths (**gamm1w**, **gamm1z**) and the Weinberg angle (**sin2w**) are treated as independent parameters. They enter an effective Born cross section and may be set directly by the user. As a special case, setting **gamm1w** to 0 reproduces the narrow-width approximation with on-shell W ’s in the intermediate state.

The bulk of the non-electromagnetic radiative corrections can be incorporated into the hard cross section by using the running QED coupling $\alpha_{QED}(4M_W^2) \approx 1/128$ at the W scale. This value is, however, *not* correct for the initial state radiation of on-shell photons, where $\alpha_{QED}(0) \approx 1/137$ has to be used. The inverse of the former value can be changed with **ahpla** and that of the latter with **ahpla0**.

The presence of initial state radiation can be toggled using the parameter **bstyle**. The supported values are 0 and 1, corresponding to no QED radiative corrections and LLA resummed initial state QED radiative corrections.

The variable **cc11** controls the number of Feynman diagrams taken into account. The default value is **.true.**, which amounts to using all diagrams shown in figures 2 and 3. Setting this variable to false restricts the calculation to only the doubly resonant (“signal”) diagrams in figure 2, also known as “CC03” diagrams.

Variable name	semantics	Default value
ebeam	e^+/e^- beam energy	250 GeV
epol	longitudinal e^- beam polarization	0
ppol	longitudinal e^+ beam polarization	0
scheme	renormalization scheme	1
ahpla	$1/\alpha_{QED}(4M_W^2)$	128
ahpla0	$1/\alpha_{QED}(0)$	137.0359895
mass1e	m_{e^\pm}	$0.51099906 \cdot 10^{-3}$ GeV
mass1w	M_{W^\pm}	80.26 GeV
gam1w	Γ_W	2.08 GeV
mass1z	M_{Z^0}	91.1884 GeV
gam1z	Γ_Z	2.492 GeV
gfermi	G_F	$1.16639 \cdot 10^{-5}$ GeV
sin2w	$\sin^2 \theta_W$	0.2310
alphas	$\alpha_{QCD}(M_W^2)$	0.12
cc11	all CC11 diagrams	.true.
floops	fermion loop contributions	.false.
coulom	Include final state coulomb corrections	.false.
ckmvus	$V_{us} = \sin \theta_C$	0.2196
ckmvcb	V_{cb}	0.0400
ckmvub	V_{ub}	0.0032

Table 1: Standard model parameters controlling WOPPER.

As a matter of convention, all gauge boson widths are treated in WOPPER as running widths (c.f. eq. (7)). However, it is well known that the inclusion of an energy-dependence in the width of the gauge bosons distorts the cancellations between the photon and Z -exchange contributions of the signal diagrams. It has been noted [30] that the cancellations may be restored by including a minimal set of higher-order diagrams, namely the fermion loop contributions to the ZWW vertex. Neglecting the masses of all fermions except for the top-quark which is assumed to be very heavy, this so-called “fermion loop scheme” amounts to replacing the Standard Model ZWW tree-level vertex by:

$$\Gamma^{ZWW} \rightarrow \Gamma_{\text{floops}}^{ZWW} = \Gamma_{\text{tree}}^{ZWW} \cdot \left(1 + i \frac{\Gamma_Z}{M_Z}\right) \quad (23)$$

The inclusion of this factor is controlled by the variable **floops**.

Since version 1.3 it is possible to choose canonical input parameters for benchmarking LEP2 Monte Carlos [4] by changing the value of **scheme**. The following values are supported:

- **scheme = 0**: “free scheme”, all parameters are taken from the input and treated as independent parameters.

Variable name	semantics	Default value
<code>acpara</code>	parameterization	0
<code>kappag</code>	κ_γ	1
<code>lamdag</code>	λ_γ	0
<code>kappaz</code>	κ_Z	1
<code>lamdaz</code>	λ_Z	0
<code>g1z</code>	g_1^Z	1
<code>g4z</code>	g_4^Z	0
<code>g5z</code>	g_5^Z	0
<code>kapzt</code>	$\tilde{\kappa}_Z$	0
<code>lamzt</code>	$\tilde{\lambda}_Z$	0
<code>acdZ</code>	δ_Z	0
<code>acxg</code>	x_γ	0
<code>acxz</code>	x_Z	0
<code>acyg</code>	y_γ	0
<code>acyz</code>	y_Z	0
<code>aczz</code>	z_Z	0

Table 2: Anomalous couplings parameters controlling WOPPER.

- `scheme` = 1 (default): “ G_F scheme”

$$\sin^2 \theta_W = \frac{\pi \alpha_{QED} (4M_W^2)}{\sqrt{2} G_F M_W^2} \quad (24)$$

$$\Gamma_W = \frac{G_F M_W^3}{\sqrt{8}\pi} \left(3 + \frac{2\alpha_{QCD}}{\pi} \right) \quad (25)$$

- `scheme` = 2: “ $\sin \theta_W^{\text{eff.}}$ scheme”

$$G_F = \frac{\pi \alpha_{QED} (4M_W^2)}{\sqrt{2} \sin^2 \theta_W M_W^2} \quad (26)$$

$$\Gamma_W = \frac{G_F M_W^3}{\sqrt{8}\pi} \left(3 + \frac{2\alpha_{QCD}}{\pi} \right) \quad (27)$$

- `scheme` = 3: “Born scheme”, tree level formulas, independent $\sin \theta_W$, G_F , $\alpha_{QED}(4M_W^2) = \alpha_{QED}(0)$ and

$$\Gamma_W = \frac{G_F M_W^3}{\sqrt{8}\pi} \left(3 + \frac{2\alpha_{QCD}}{\pi} \right) \quad (28)$$

- `scheme` = -1, -2, -3: same as the positive values, except for Γ_W which is not calculated from the standard model expression but taken from `gamm1w` instead.

Variable name	semantics	Default value
<code>cutmin</code>	minimum W^\pm virtuality	0 GeV
<code>cutmax</code>	maximum W^\pm virtuality	$\sqrt{s} = 2E_{Beam}$
<code>nevent</code>	Number of events	10000
<code>cc</code>	apply canonical cuts	.false.
<code>cclvl</code>	level of canonical cuts	0
<code>ccver</code>	version of canonical cuts	1
<code>bstyle</code>	Key for QED radiation	1
<code>circe</code>	beamstrahlung	.false.
<code>ciracc</code>	accelerator	2 (TESLA)
<code>cirver</code>	version	1
<code>cirrev</code>	revision	19960401
<code>circht</code>	chattines	1
<code>epsiln</code>	Internal infrared cutoff	10^{-5}
<code>qcdmc</code>	Key for QCD Monte Carlo	0
<code>rangen</code>	Random number generator	1
<code>rseed</code>	Random number seed	54217137
<code>rlux</code>	‘Luxury’ of generator	3
<code>errmax</code>	maximum error count	100
<code>verbos</code>	verbosity	0
<code>runid</code>	run identification	
<code>stdin</code>	standard input	5
<code>stdout</code>	standard output	6
<code>stderr</code>	standard error	6

Table 3: Technical parameters controlling WOPPER.

4.2 Anomalous couplings

The parameterization of anomalous WWZ and WWZ couplings in table 2 is controlled by the `acpara` variable:

- `acpara` = 0: no anomalous couplings at all. During initialization, κ_γ , λ_γ , κ_Z , λ_Z , g_1^Z , g_4^Z , g_5^Z , $\tilde{\kappa}_Z$, $\tilde{\lambda}_Z$ will be reset to their standard model values.
- `acpara` = 1: anomalous couplings in the Hagiwara et al. [8] parameterization, using the values of κ_γ , λ_γ , κ_Z , λ_Z , g_1^Z , g_4^Z , g_5^Z , $\tilde{\kappa}_Z$, $\tilde{\lambda}_Z$ specified in the variables from table 2.
- `acpara` = 2: anomalous couplings in the $(\delta_Z, x_\gamma, x_Z, y_\gamma, y_Z, z_Z)$ parameterization. The corresponding Hagiwara et al. parameters

$$\kappa_\gamma = 1 + x_\gamma \quad (29)$$

$$\lambda_\gamma = y_\gamma \quad (30)$$

$$\kappa_Z = 1 + (x_Z + \delta_Z) \tan \theta_W \quad (31)$$

$$\lambda_Z = y_Z \tan \theta_W \quad (32)$$

$$g_1^Z = 1 + \delta_Z \tan \theta_W \quad (33)$$

$$g_4^Z = 0 \quad (34)$$

$$g_5^Z = -\frac{s}{M_W^2} z_Z \tan \theta_W \quad (35)$$

$$\tilde{\kappa}_Z = 0 \quad (36)$$

$$\tilde{\lambda}_Z = 0 \quad (37)$$

will be used in the Monte Carlo.

The relation (35) between g_5^Z and z_Z is only approximate. z_Z is defined as the coefficient in the higher dimensional operator

$$\mathcal{L}_{\mathcal{CP}} = \frac{e z_Z}{M_W^2} \partial_\mu \tilde{Z}_{\nu\rho} (\partial^\nu W^{-\rho} W^{+\mu} - \partial^\nu W^{-\mu} W^{+\rho} + \partial^\nu W^{+\rho} W^{-\mu} - \partial^\nu W^{+\mu} W^{-\rho}) \quad (38)$$

In the approximation of massless final state fermions and equal invariant mass of the intermediate W 's, the relation (35) can be shown. Radiative corrections cause a further deviation, because of the change in s . Until future version of WOPPER will support z_Z directly, (35) is an excellent approximation.

It should be noted that even a small value of z_Z will have a strong effect at NLC energies, because of the s -factor in (35) induced by the additional mass dimensions in $\mathcal{L}_{\mathcal{CP}}$. The natural value of z_Z will therefore be much smaller than that of the other parameters.

4.3 Cuts

In the present version 1.5 of WOPPER, only cuts in the virtualities of the intermediate W 's are implemented in the event generation:

- **cutmin**: minimum virtuality of the intermediate $W^{\pm s}$,
- **cutmax**: maximum virtuality of the intermediate $W^{\pm s}$.

The cuts in virtualities have to satisfy the following conditions:

$$0 \leq \text{cutmin} < \text{cutmax} \leq \sqrt{s} = 2E_{\text{Beam}} \quad (39)$$

A value of 0 for **cutmax** will automatically be reset to the available maximum, namely $2E_{\text{Beam}}$.

Since version 1.3 it is possible to apply the canonical cuts for benchmarking LEP2 Monte Carlos [4] to the event record by setting **cc** to **.true..** These cuts will be reflected in the calculated total cross section.

4.4 Beamstrahlung

WOPPER can be linked with the CIRCE library [31] to include the effects of the beam-beam interaction at a linear collider. If the parameter **circe** is set to **.true.**, the momenta of the incoming electrons and positrons will be distributed according to the version (**cirver**) and revision (**cirver**) of the CIRCE parameterization of a particular accelerator design class(**ciracc**).

4.5 Monte Carlo Parameters

The remaining, more technical Monte Carlo parameters should be almost self explaining. Since our branching algorithm automatically includes soft photon exponentiation, the results will not depend on the value of the internal infrared cutoff `epsiln` (which is measured in units of the beam energy), provided it is kept *well below* the experimental energy resolution. However, it is not advisable to set it many orders of magnitude lower than the default value, because this may result in too high photon multiplicities that will overflow internal tables.

A note on the random number generators available: the default value 1 of the parameter `rangem` corresponds to the standard `RANMAR` [32] generator, that has been the generator of choice for quite some time. Recently, the quality of the random numbers generated by `RANMAR` has been questioned and unwanted correlations have been found, that caused large systematic errors in solid state physics simulations [33]. A superior variation `RANLUX` has been proposed [34], which is however *much* slower. If `WOPPER` has been linked with the `CERN` library, setting `rangem` to 2 switches to `RANLUX` which can be used at the 5 “luxury levels” 0 to 4. At the highest “luxury levels”, `RANLUX` will be rather slow, however.

However, since event generation involves a lot of decisions that effectively randomize the subsequences used by themselves, we do not expect that the correlations in `RANMAR` have any significant effect on the event samples generated by `WOPPER`. The `RANLUX` option has been added to `WOPPER` for some experimentation only. It is left in only because there is no particular reason for throwing it out again.

An even more interesting option is the random number generator recently proposed by Donald Knuth [35]. This generator is selected by setting `rangem` to 3. It generates 30-bit integers with the following desirable properties:

- the bit stream passed all the tests from George Marsaglia’s “diehard” suite of tests for random number generators [36] (the result of the “birthday-spacing” test has to be used with great care, because the position of the least significant bit of the 30-bit words varies if the bit stream is distributed into 32-bit words).
- it can be implemented with portable signed 32-bit arithmetic (`Fortran` can’t do unsigned arithmetic).
- it can create at least $2^{30} - 2$ independent sequences, which are selected by a 30-bit integer seed value.
- it is very fast.

The default value of `rangem` is still 1, but all users are encouraged to give the Knuth generator a try.

4.6 QCD Parameters

The parameters for `JETSET` should be accessed through `WOPPER`’s `lugive` command, which is translated directly to `JETSET`’s `LUGIVE()` subroutine. See the `JETSET` manual [26] for a comprehensive description of the available parameters and their effects.

WOPPER	HERWIG	semantics	Default value
hwqcd1	QCDLAM	Λ_{QCD}/GeV	0.18
hwrms1	RMAS(1)	m_d/GeV	0.32
hwrms2	RMAS(2)	m_u/GeV	0.32
hwrms3	RMAS(3)	m_s/GeV	0.5
hwrms4	RMAS(4)	m_c/GeV	1.8
hwrms5	RMAS(5)	m_b/GeV	5.2
hwrms6	RMAS(6)	m_t/GeV	100.00
hwrms0	RMAS(13)	m_q^{eff}/GeV	0.75
hwvqcu	VQCUT	Quark virtuality cutoff	0.48
hwvgcu	VGCUT	Gluon virtuality cutoff	0.10
hwvpcu	VPCUT	Photon virtuality cutoff	-1.00
hwclma	CLMAX	Max. cluster mass parameter	3.35
hwpspl	PSPLT	Split cluster parameter	1.00
hwqdiq	QDIQK	Max. scale for $g \rightarrow$ diquark	0.00
hwpdic	PDIQK	$g \rightarrow$ diquark rate parameter	5.00
hwqspa	QSPAC	Spacelike evolution cutoff	2.50
hwptrm	PTRMS	Intrinsic p_T	0.00

Table 4: HERWIG parameters accessible from WOPPER.

Since HERWIG does not sport the equivalent of the LUGIVE() routine, its parameters have to be accessed through the standard WOPPER access mechanisms. Tables 4 and 5 provide a list of the available HERWIG parameters and the names under which they are known to WOPPER. See the HERWIG manual [27] for a comprehensive description of the effects of these parameters.

ARIADNE doesn't supply a high level parameter changing interface (like LUGIVE()) as well. Since the tunable parameters are more copious than in the case of HERWIG, we have refrained from making them accessible through the WOPPER parameter interface. Users who wish to change ARIADNE parameters are invited to add a call to their parameter changing routine to `wwaria()`. The standard ARIADNE tuning sets can however be accessed with the `artune` command, which passes its argument to the ARTUNE() routine.

5 FORTRAN-77 Interface

WOPPER version 1.5 provides two application program interfaces on different levels. The higher (preferred) level consists of the command interpreter `wwdcm` that accepts commands in form of `character*(*)` strings. This driver communicates with the analyzer `hepawk` [29] by default. The lower level consists of two FORTRAN-77 subroutine calls: `wwpsrv` and `wopper`.

WOPPER	HERWIG	semantics	Default value
hwipri	IPRINT	Printout option	1
hwmaxp	MAXPR	Max. printouts	0
hwmaxe	MAXER	Max. errors	10
hwlwev	LWEVT	Event output unit	0
hwlrslu	LRSUD	Sudakov input unit	0
hwlsu	LWSUD	Sudakov output unit	77
hwsudo	SUDORD	Sudakov order in α_S	1
hwnrn1	NRN(1)	First random seed	17673
hwnrn2	NRN(2)	Second random seed	63565
hwazso	AZSOFT	Soft gluon azimuthal correlations	.true.
hwazsp	AZSPIN	Gluon spin azimuthal correlations	.true.
hwb1li	B1LIM	B -cluster \rightarrow 1 hadron parameter	0.0

Table 5: Technical HERWIG parameters accessible from WOPPER.

```
* wopperappl.f
...
call wwdcmd ('set ebeam 95')           select  $\sqrt{s} = 190\text{ GeV}$ 
call wwdcmd ('set acpara 2')          select anomalous coupling
call wwdcmd ('set acdz 0.01')          $\delta_Z = 0.01$ 
...
call wwdcmd ('init')                  initialize the generator
call wwdcmd ('generate 10000')        generate 10000 events
...
call wwdcmd ('close')                 cleanup
...
```

Figure 4: Higher level FORTRAN-77 interface

5.1 Higher Level Interface

The simple commands understood by `wwdcmd` are (here keywords are typeset in typewriter font and variables in italics; vertical bars denote alternatives)

- **initialize**
Force initialization of WOPPER and write an initialization record into the `/hepevt/` event record, which should trigger the necessary initializations in the analyzer.
- **generate** $[n]$
Generate `nevent` events and call `hepawk` to analyze them. If the optional parameter n is supplied, `nevent` is set to its value.
- **close**

Write a termination record to `/hepevt/`, which should trigger the necessary cleanups in the analyzer.

- **statistics**

Print performance statistics (this is usually only useful for the WOPPER developers, who are tuning internal parameters).

- **quit**

Terminate WOPPER without writing a termination record.

- **exit|bye**

Write a termination record and terminate WOPPER.

- **set *variable ival|rval***

Set physical or internal parameters. See the tables 1 and 3 for a comprehensive listing of all variables. For example, the command `'set ahpla 127.0'` will set the QED fine structure constant to $1/127$.

- **print *variable|all***

Print the value of physical or internal variables. `print *` causes a listing of all variables known to WOPPER and `print prefix*` causes a listing of all variables starting with the given prefix.

- **debug|nodebug *flag***

Toggle debugging flags.

- **testran**

Test the portability of the random number generator. We use a generator of the Marsaglia-Zaman variety [32], which should give identical results on almost all machines.

- **banner**

Print a string identifying this version of WOPPER.

- **echo *message***

Print *message* on standard output.

- **lugive *string***

Pass *string* to JETSET's LUGIVE() routine. See [26] for details.

- **artune *string***

Pass *string* to ARIADNE's ARTUNE() routine. See [28] for details.

Unique abbreviations of the keywords are accepted, i.e. `'g 1000'` generates 1000 events. The tokens are separated by blanks. Blank lines and lines starting with a `#` are ignored and may be used for comments. For portability, only the first 72 characters of each line are considered.

On UNIX systems WOPPER reads the default startup files `.wopper` in the user's home directory and the current directory, if they exist.

```

* wwdcmd.f
  subroutine wwdcmd (cmdlin)
  character*(*) cmdlin
  ...
  else if (cmdlin.eq.'init')
    call wopper (0)
    call hepawk ('scan')
  else if (cmdlin.eq.'generate')
    do 10 n = 1, nevent
      call wopper (1)
      call hepawk ('scan')
10    continue
  else if (cmdlin.eq.'close')
    call wopper (2)
    call hepawk ('scan')
  else
    ...
  end

```

initialize WOPPER
print initialization record

generate an event
analyze the event

get total cross section, etc.
finalize analysis

Figure 5: Event generation loop

5.2 Lower Level Interface

The subroutine `wopper` (code) has a single integer parameter. The parameter `code` is interpreted as follows:

- 0: initialize the generator and write an initialization record to `/hepevt/`.
- 1: generate an event and store it in `/hepevt/`. If WOPPER has not been initialized yet, the necessary initializations are performed, but no initialization record is written.
- 2: perform final calculations and write the results to `/hepevt/`.

Figure 5 displays excerpts from a simplified version of `wwdcmd` that make the correspondences between the two levels of the **FORTRAN-77** interface explicit.

WOPPER's parameters can be accessed on the lower level by the subroutine `wwpsrv` (`result`, `action`, `name`, `type`, `ival`, `rval`, `dval`, `lval`). The parameter is specified by its (lowercase) name in the `character*(*)` string `name`. The string `action` is either `'read'` or `'write'` corresponding to whether the parameter is to be inspected or modified. The type of the parameter (`'int'`, `'real'`, `'dble'`, or `'lgcl'`) is specified in `type`; it is an input parameter for `'read'` and an output parameter for `'write'`. Depending on this type the value is passed in `ival`, `rval`, `dval`, or `lval`, respectively. The following error codes will be returned in the string `result`: `' '`: no error, `'enoarg'`: invalid `action`, `'enoent'`: no such parameter, `'enoperm'`: permission denied, and `'enotype'`: invalid `type`.

The protection scheme implemented with this parameter handling has been described in [20]. Its main purpose is to guarantee consistency of user defined and computed parameters in the generation phase of the Monte Carlo.

```

usage: $0 [options] [var=val] ...

var=val                                assign VALue to WOPPER VARIable

-e energy, --beam-energy energy: beam ENERGY (= sqrt(s)/2) in GeV
-s roots, --roots roots:             sqrt(s) (= 2 beam energy) in GeV
-n num, --events num:                generate NUM events
-r num, --report num:                write a summary record every NUM events
-H script, --hepawk script:          use hepawk SCRIPT

-q yes|no, --QED yes|no:              apply QED raditiative corrections
-Q mc, --QCD mc:                     use QCD Monte Carlo MC
-a mode, --ac mode:                  select anomalous couplings MODE
-f file, --file file:                source FILE with variable settings
-R rng, --rangen rng:                use Random Number Generator
-S seed, --seed seed:                random number SEED

-k, --keep:                           keep the temporary run directory
-o file, --output file:               write output to FILE (implies -p FILE)
-p file, --preserve file:             salvage FILE from temporary run directory
-x cmd, --sed cmd:                   filter hepawk script through sed CoManD
-t dir, --tmpdir dir:                use DIR as temporary run directory
-b bin, --binary bin:                use BIN as WOPPER binary

-h, --help:                           this message

```

Figure 6: Command line options of the `wrun` script for WOPPER on UNIX systems.

5.3 Command Line Interface for UNIX Systems

The distributed version of the WOPPER main program reads commands from the standard input channel and passes them directly to `wwdcmd`. WOPPER writes results to the standard output channel, user supplied analysis routines may write additional files with histograms, etc.

Using no other operating system services than the standard input channel for input makes the program very portable. At the same time, it is not the most user friendly approach for repetitive tasks, like scanning parameter sets. Therefore we provide a shell script `wrun`, which can be used to control wopper from the UNIX commandline.

In figure 6 the usage message of `wrun` is shown. Variable can be set on the command line. The `wrun` script will create an appropriate input file for WOPPER:

`<var>=<value>`: sets the WOPPER variable `<var>` to the value `<value>`. Examples: `cc11=false`, `sin2w=0.23103`, etc.

Some of these variables can be changed by an option as well:

`-e <energy>` or `--beam-energy <energy>`: set the beam energy, this is equivalent to `ebeam= E_B` .

`-n <num>` or `--events <num>`: set the number of events, this is equivalent to `nevent= n` .

- r $\langle num \rangle$ or --report $\langle num \rangle$: write a summary record every everz $\langle num \rangle$ events, this is equivalent to **report=n**.
- S $\langle seed \rangle$ or --seed $\langle seed \rangle$: set the seed of the random number generator, this is equivalent to **rseed=n**.

For some variables symbolic names or convenience translations are available:

- s $\langle roots \rangle$ or --roots $\langle roots \rangle$: set the center of mass energy \sqrt{s} , this is equivalent to **ebeam= $\sqrt{s}/2$** .
- q yes|no or --QED yes|no: toggle electromagnetic radiative corrections, --q yes is equivalent to **bstyle=1** and -q no is equivalent to **bstyle=0**.
- Q $\langle mc \rangle$ or --QCD $\langle mc \rangle$: select a hadronization Monte Carlo: $\langle mc \rangle$ can be **parton**, **jetset**, **herwig** or **ariadne**.
- a $\langle mode \rangle$ or --ac $\langle mode \rangle$: select an anomalous couplings parameterization: $\langle mode \rangle$ can be **no** or **SM** for no anomalous couplings, **Hagiwara**, **kappa**, **lambda** for the κ - λ parameterization or **delta** for the δ - x - y parameterization.
- R $\langle rng \rangle$ or --rangen $\langle rng \rangle$: select a random number generator: $\langle rng \rangle$ can be **ranmar**, **ranlux** or **Knuth**.

The behaviour of the script can be changed with the following options:

- b $\langle bin \rangle$ or --binary $\langle bin \rangle$: select a different WOPPER binary.
- o $\langle file \rangle$ or --output $\langle file \rangle$: write the WOPPER output to $\langle file \rangle$
- t $\langle dir \rangle$ or --tmpdir $\langle dir \rangle$: specify a temporary run directory. By default, WOPPER will be run in a temporary directory with a unique name.
- p $\langle file \rangle$ or --preserve $\langle file \rangle$: copy the file $\langle file \rangle$ to the starting directory before deleting the temporary run directory.
- k or --keep: don't delete the temporary run directory.

The following options are useful if **hepawk** [29] is used for event analysis:

- H $\langle script \rangle$ or --hepawk $\langle script \rangle$: select a **hepawk** script.
- x $\langle cmd \rangle$ or --sed $\langle cmd \rangle$: filter the **hepawk** script through the UNIX stream editor **sed**. This is particularly useful for changing the name of the file in which **hepawk** saves its histograms. For example, if the script contains the command **save("@@@")**; , the option **-x s/@@@/foo.hbook/** will cause **hepawk** to save the histograms in **foo.hbook**.

This shell script can be used to run test suites easily. For example, the tests in [37] can be run with the shell script in figure 7 provided that the file **ac.hepawk** contains an appropriate **hepawk** script.

```

#!/bin/sh
run () {
    ./wrun -a delta ac$1 -q $2 -e 95.0 -n 100000 cc11=false \
        scheme=-2 ahpla=128.07 sin2w=0.23103 mass1z=91.1888 \
        mass1w=80.23 gamm1z=2.4974 gamm1w=2.08 \
        -o ac.$3.out -p ac.$3.hbook -H ac.hepawk \
        -x s/ac.hbook/ac.$3.hbook/
}
for q in 0 1; do
    run acpara=0 $q sm__.$q$q
    for d in 2 5; do
        for v in dz xg xz yg yz zz; do
            for s in - +; do
                run $v=${s}0.$d $q $v$s$d.q$q
            done
        done
    done
done
exit 0

```

Figure 7: Running tests for various anomalous couplings with **WOPPER** on UNIX systems.

6 Conclusions

We have presented version 1.5 of the Monte Carlo event generator **WOPPER** for W pair production and decays into four fermions at high energy e^+e^- colliders. The distinguishing feature of **WOPPER** is the inclusion of higher order electromagnetic corrections including soft photon exponentiation and explicit generation of exclusive hard photons. In contrast to fixed order calculations which have to be exponentiated by hand, **WOPPER** handles the multiphoton effects explicitly.

The present version does not contain weak corrections. Forthcoming versions of the Monte Carlo generator will include weak corrections in the framework of effective Born cross sections [38].

Acknowledgments

Thomas Mannel and Angelika Himmeler have contributed to earlier versions of **WOPPER**. We are grateful to the members of the W -physics and event generator working groups of the 1995 LEP2 workshop for appreciating our efforts.

A Distribution

The latest release of **WOPPER** is available by anonymous ftp from

crunch.ikp.physik.th-darmstadt.de

in the directory

pub/ohl/wopper

or on the World Wide Web at the URL

`\protect\vrule width0pt\protect\href{http://crunch.ikp.physik.th-darmstadt.de/monte-carlos.`

Important announcements (new versions, fatal bugs, etc.) will be made through the mailing list

`wopper-announce@crunch.ikp.physik.th-darmstadt.de`

Subscriptions can be obtained from

`majordomo@crunch.ikp.physik.th-darmstadt.de`

(send a message consisting of `help` to `majordomo` for instructions on how to subscribe, don't send such messages to the list itself).

B Installation

WOPPER is distributed in PATCHY format [39]. Plain FORTRAN-77 versions can be made available on request. The source conforms to ANSI X3.9-1978, with the exception of use of the following rather common extensions:

- `implicit none` (may be disabled),
- `double complex` arithmetic (essential), and
- `do ... end do` constructs.

Therefore, it should run without modifications on all platforms.

B.1 UNIX Systems

On UNIX systems, the configuration, compilation and installation can be performed automatically according to the following sequence:

```
$ ./configure
$ make
$ make install
```

Optional interface code for external hadronization Monte Carlos, analysis routines, etc. can be selected by giving command line options to the `configure` script. Figure 8 shows some of these command line options. This `configure` script has been created by the popular GNU Autoconf [40] package and should work on all UNIX variants.

If the `--with-hepawk` option has been specified in the `configure` step, a self test can be performed by `make test`.

B.2 Non-UNIX Systems

For non-UNIX systems configuration and compilation has to be performed manually from the CARDS file and the `cradles`.


```

Usage: configure [options] [host]
Options: [defaults in brackets after descriptions]
Configuration:
  --cache-file=FILE      cache test results in FILE
  --help                  print this message
  --no-create              do not create output files
Host type:
  --build=BUILD           configure for building on BUILD [BUILD=HOST]
  --host=HOST              configure for HOST [guessed]
  --target=TARGET         configure for TARGET [TARGET=HOST]
Features and packages:
  --disable-FEATURE       do not include FEATURE (same as --enable-FEATURE=no)
  --enable-FEATURE[=ARG] include FEATURE [ARG=yes]
  --with-PACKAGE[=ARG]    use PACKAGE [ARG=yes]
  --without-PACKAGE       do not use PACKAGE (same as --with-PACKAGE=no)
--enable and --with options recognized:
  --with-g77              use GNU Fortran 77
  --enable-verbose-patchy display all patchy output
  --enable-internal       do not use this!
  --enable-notime         do not use timing functions
  --enable-pedantic       no IMPLICIT NONE
  --with-libpath=PATH     use PATH for libraries
  --with-srcpath=PATH     use PATH for source files (CARs)
  --with-hepawk           use HEPAWK for event analysis
  --with-jetset           use JETSET hadronization
  --with-herwig           use HERWIG hadronization
  --with-ariadne          use ARIADNE hadronization
  --with-circe            use CIRCE for beamstrahlung
  --with-ranlux           use RANLUX generator
  --with-cernlib          use CERNLIB
  --with-lepbench         link in the LEP2 benchmarking code
  --enable-debug          compile for debugging
  --enable-paper-a4       use European (A4) paper
  --enable-paper-us       use US (letter) paper

```

Figure 8: Some of the comandline options of the `configure` script for WOPPER on UNIX systems.

C External Symbols: Common Blocks and Sub-routines

To avoid possible name clashes with other packages, all external symbols exported by WOPPER proper begin with the two letters `WW`, except for the routine `wopper` itself and the `/hepevt/` common block.

- Common Blocks:

The following common blocks are used by WOPPER:

- `/hepevt/`, `/hepspn/`: standard common blocks for passing generated events [2]
- `/wwpcom/`: main parameter common block, holds all physical parameters. Application programs should access this common block through

the `wwpsrv` routine

- `/wwcbrn/`: internal parameters used for born cross section
- `/wwcdec/`: internal parameters used for W decays
- `/wwcevt/`: internal parameters used for event generation
- `/wwcsta/`: statistics
- `/wwctri/`: storage for keyword lookup

- Driver Program:

- `wwdriv`: sample main program, which reads commands from standard input and feeds them into `wwdcmnd`
- `wwdloo`: command loop, reading command from a terminal or file and executing them
- `wopper`: the low level entry point into the generator for application programs
- `wwdcmnd`: WOPPER's command interpreter, the preferred entry point for application programs. Executes a single command
- `wwdlxi`, `wwdlxd`, `wwdlxs`: Utility routines: tokenization of input
- `wwdsig`: UNIX signal handler
- `isatty`: check if this job is run interactively

- Parameter Management:

These routines are used to control the parameters common block `/wwpcom/`:

- `wwpsrv`: server handling parameter changing requests
- `wwpini`: block data supplying default values
- `wwpprn`: print parameters

- Initialization:

- `wwinit`: main entry point for initializations
- `wwigsw`: initialization of electroweak parameters
- `wwicut`: initialization of internal Monte Carlo parameters
- `wwibmx`: find maximum of Born cross section
- `wwibmy`: wrapper for `wwuamo`
- `wwibn`: auxiliary function for finding maximum of on-shell cross section
- `wwibns`: auxiliary function for finding maximum of cross section for symmetric virtualities
- `wwibna`: auxiliary function for finding maximum of cross section for one W on-shell
- `wwibnv`: auxiliary function for finding maximum of cross section for general case

- Final calculations:

- `wwclos`: calculate total cross section, errors and close the generator
- `wwstat`: statistics

- Hard Subprocess Generation:

- **wwgen**: main entry point for hard subprocess generation
- **wwgcfs**: selection of initial and final state quantum numbers
- **wwgww**: generation of angular distribution of pseudo W 's
- **wwgppr**: generate four-momenta of pseudo W 's
- **wwgdec**: generate final state fermions from pseudo W decays
- **wwdqfl**: select quark flavors in W decay
- Branching:
 - **wwbini**: generates the initial state photon radiation
- Cross Sections:
 - **wwheli**: coefficients of the helicity amplitude decomposition
 - **wwxtot**: total off-shell cross section
 - **wwxint**: auxiliary function for integration over pseudo W masses
 - **wwxdif**: differential W cross section
 - **wwxdmx**: maximum estimate of differential W cross section
 - **wwxhel**: helicity amplitude for $e^+e^- \rightarrow 4f$
 - **wwxhmx**: maximum estimate of helicity amplitude for $e^+e^- \rightarrow 4f$
- Accessing `/hepevt/`:
 - **wweni**: enter identification of Monte Carlo and run
 - **wweens**: write summary record to `/hepevt/`
 - **wwuent**: enter one particle into `/hepevt/`
 - **wwenul**: enter null particle into `/hepevt/`
 - **wwenew**: clear `/hepevt/`
 - **wwecpy**: copy a `/hepevt/` entry
 - **wwesft**: shift `/hepevt/` entries
 - **wwepsh**: push `/hepevt/` onto a stack (one level deep)
 - **wwepop**: pop `/hepevt/` from a stack
- Hadronization:
 - **wwpart**: leave partons alone
 - **wwlund**: JETSET interface code
 - **lu4frm**: JETSET interface code
 - **wwhwig**: HERWIG interface code
 - **hw4fdo**, **hw4fin**, **hw4fgo**, **hw4fcc**, **hw4fcs**: HERWIG interface code
 - **hwaend**: HERWIG abnormal end routine
 - **wwaria**: ARIADNE interface code
- Random Numbers:

- `wwrgen`: returns a double precision uniform deviate
- `wwurng`: (subroutine version)
- `wwrmz`: random number generator RANMAR
- `wwrtst`: test the portability of the random number generator
- `wwrtmz`: test RANMAR
- `wwrkng`: Knuth's random number generator
- `wwrknu`: Knuth's random number generator (buffered version)
- `wwrkns`: seed Knuth's random number generator
- `wwrknl`: set luxury for Knuth's random number generator
- `wwrkni`: initialize Knuth's random number generator
- `wwrknt`: test Knuth's random number generator
- Utilities:
 - `wwumsg`: messages and error exit
 - `wwulwr`: convert input to lower case
 - `wwuboo`: boost a four vector
 - `wwutim`: still available CPU time for this job
 - `wwuamo`: multidimensional minimization
 - `wwumin`: onedimensional minimization
 - `wwuons`: Gram-Schmidt procedure
 - `wwuort`: another Gram-Schmidt procedure
- Canonical cuts:
 - `adloth`: apply canonical cuts in `/hepevt/`
 - `adloip`: inner product of vectors in `/hepevt/`
 - `adloan`: angle to beam in `/hepevt/`
 - `adload`: add four momenta in `/hepevt/`
- LEP2 benchmarks [4]:

(optional, selected with `configure --with-lepbench`)

 - `hepawk`: main analysis routine
 - `lbfill`: fill a histogram
 - `lbcheb`: Chebyshev moments
 - `lbpowr`: power moments
 - `lbprin`: print output
 - `lblsct`: select event
- Keyword search:

(using the dynamic tries described in [41])

- `wwtins`: insert a new keyword
- `wwtlup`: look up a (possibly abbreviated) keyword
- `wwtnew`: insert new a node into the trie
- `wwtlen`: calculate length of keyword
- `wwtc2a`: convert keyword from `character(*)` to `integer(*)`

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Test Run

WOPPER version 1.5 is distributed together with a sample command file and `hepawk` script, which are given below. To run this example, the user will need to link WOPPER with the CERN library, because histogramming is done by HBOOK [42].

The file `sample.wopper` is read from standard input (unit `stdin`, which is initialized to 5), and `sample.hepawk` is read from the file `SCRIPT` (i.e. under MVS from the file which has been allocated to the `DDNAME SCRIPT` and under UNIX from the file `script` or from the value of the environment variable `SCRIPT`).

`sample.wopper`

Here is a simple WOPPER command file, setting up parameters and generating 10000 events.

```
# sample.wopper -- sample WOPPER command file

# parameters
set ebeam 87.5

# run
init
gen 10000
close
quit
```

`sample.hepawk`

This is a small `hepawk` [29] script that counts the muons from the W decays and plots a histogram of their energy distribution. The first generated event is dumped to illustrate the usage of the `/hepevt/` common block.

```
# sample.hepawk -- sample HEPARK analyzer for WOPPER.

BEGIN {
  printf ("\nWelcome to the WOPPER test:\n");
  printf ("*****\n\n");
  printf ("Monte Carlo Version: %s\n", REV);
  printf ("                Run: %d\n", RUN);
  printf ("                Date: %s\n\n", DATE);
```

```

E_max = 100;
N_chan = 50;
h_muon_energy
    = book1 (0, "Muon-energy", N_chan, 0, E_beam);
nr_muons = 0;          # initialize counter
dumped_an_event = 0;
}

{
    if (dumped_an_event == 0) {
        dump ("vs");          # Dumping first event
        dumped_an_event++;
    }

    for (@p in LEPTONS)
        if (abs(@p:id) == _pdg_muon) {
            fill (h_muon_energy, @p:p:E);
            nr_muons++;
        }
}

END { # Dump some numbers
    printf ("\nRESULTS:\n*****\n\n");
    printf ("Total events:      %d, total cross section: %g pb\n",
            NEVENT, XSECT * 1e9);
    printf ("Number of muons: %d\n\n", nr_muons);
    plot();
    printf ("\ndone.\n");
}

```


sample.output

The following output should result from the input files above, up to small round-off errors and different FORTRAN-77 default output formats.

```
wwdcmnd: message: Starting WOPPER, Version 1.05/00, (build 960530/2055)
wwdcmnd: message: ... linked with ARIADNE.
wwdcmnd: message: ... linked with CIRCE.
wwdcmnd: message: ... linked with HEPAWK.
wwdcmnd: message: ... linked with HERWIG.
wwdcmnd: message: ... linked with JETSET.
wwdcmnd: message: ... enabled RANLUX.
hepawk: message: starting HEPAWK, Version 1.6
wwigsw: message: *****
wwigsw: message: "GF scheme" selected:
wwigsw: message: Using GFERMI and ALPHA as input, calculating SIN2W.
wwigsw: message: Using derived W width.
wwigsw: message: Parameters used in this run:
wwigsw: message: AHPLA = 128.00000 ( = 1/alpha(2 M_W) )
wwigsw: message: SIN2W = 0.23098 (effective mixing angle)
wwigsw: message: GFERMI = 0.116639E-04 GeV**(-2)
wwigsw: message: ALPHAS = 0.12000
wwigsw: message: GAMM1W = 2.08780 GeV (S.M. value, used)
wwigsw: message: CKMVUS = 0.21960 CKM Matrix (Cabibbo angle)
wwigsw: message: CKMVCB = 0.04000 CKM Matrix
wwigsw: message: CKMVUB = 0.00320 CKM Matrix
wwigsw: message: Z-e-e couplings:
wwigsw: message: g_V = -0.01414
wwigsw: message: g_A = -0.18586
wwigsw: message: W-e-nu coupling:
wwigsw: message: g = 0.23050
wwigsw: message: Z-W-W coupling:
wwigsw: message: g_ZWW = 0.57171
wwigsw: message: gamma-W-W coupling:
wwigsw: message: g_gWW = 0.31333
wwigsw: message: *****
wwigsw: message: Using standard model triple gauge couplings.
wwigsw: message: Using energy-dependent width for W and Z propagators.
wwigsw: message: Including "CC11"-type background diagrams.
wwigsw: message: Including initial state radiation (leading logs).
wwigsw: message: No Coulomb correction.
wwigsw: message: *****
wwinit: message: Selected parton level events.
```

Welcome to the WOPPER test:

Monte Carlo Version: v01.05 (May 30 00:00:00 1996)

Run: 1035996352

Date: May 30 20:57:00 1996

=====

Dumping the event record for event # 1

There are 13 entries in this record:

```

Entry # 1 is an incoming (HERWIG convention) electron
p: (0.8750E+02; 0.0000E+00, 0.0000E+00, 0.8750E+02), m: 0.0000E+00
-----
Entry # 2 is an incoming (HERWIG convention) positron
p: (0.8750E+02; 0.0000E+00, 0.0000E+00, -.8750E+02), m: 0.0000E+00
-----
Entry # 3 is the CMS system (HERWIG convention)
p: (0.1750E+03; 0.0000E+00, 0.0000E+00, 0.0000E+00), m: 0.1750E+03
-----
Entry # 4 is a null entry.
-----
Entry # 5 is a null entry.
-----
Entry # 6 is a null entry.
-----
Entry # 7 is reserved for model builders.
-----
Entry # 8 is reserved for model builders.
-----
Entry # 9 is an existing photon
p: (0.1554E+00; 0.6972E-03, -.1679E-03, -.1554E+00), m: 0.0000E+00
The mother is the positron # 5.
-----
Entry # 10 is an existing muon-neutrino
p: (0.5820E+02; 0.5040E+02, 0.2417E+02, -.1620E+02), m: 0.0000E+00
The first mother is the W+ # 7.
The other mother is the anti-muon # 11.
-----
Entry # 11 is an existing anti-muon
p: (0.2788E+02; -.2410E+02, -.6728E+01, 0.1229E+02), m: 0.1057E+00
The first mother is the W+ # 7.
The other mother is the muon-neutrino # 10.
-----
Entry # 12 is an existing muon
p: (0.4687E+02; -.2813E+00, -.3362E+02, 0.3265E+02), m: 0.1057E+00
The first mother is the W- # 8.
The other mother is the anti-muon-neutrino # 13.
-----
Entry # 13 is an existing anti-muon-neutrino
p: (0.4191E+02; -.2602E+02, 0.1617E+02, -.2859E+02), m: 0.0000E+00
The first mother is the W- # 8.
The other mother is the muon # 12.
=====

```

RESULTS:

Total events: 10000, total cross section: 13.06 pb
 Number of muons: 2195

1Muon-energy

HBOOK ID = 1

DATE 30/05/96

172						2	
168						X	
164						X	
160					7	X	
156					X	X	
152					X5	X5	
148					XX	XX	
144					XX2XX		
140					2	XXXXX	
136					7X7XXXXX		
132					XXXXXXXX		
128					XXXXXXXX		
124					XXXXXXXXX7		
120					XXXXXXXXXX		
116					XXXXXXXXXX		
112					2	XXXXXXXXXX	
108					X	7XXXXXXXXXX	
104					5X	XXXXXXXXXX	
100					XX	XXXXXXXXXX	
96					7	XXXXXXXXXXXXXXXX	
92					X	XXXXXXXXXXXXXXXX	
88					X	XXXXXXXXXXXXXXXX	
84					X	XXXXXXXXXXXXXXXX	
80					X	XXXXXXXXXXXXXXXX	
76					X2	XXXXXXXXXXXXXXXX	
72						XXXXXXXXXXXXXXXX	
68						XXXXXXXXXXXXXXXX	
64						XXXXXXXXXXXXXXXX	
60						XXXXXXXXXXXXXXXX	
56						XXXXXXXXXXXXXXXX	
52						XXXXXXXXXXXXXXXX	
48						XXXXXXXXXXXXXXXX	
44						XXXXXXXXXXXXXXXX	
40						XXXXXXXXXXXXXXXX	
36						XXXXXXXXXXXXXXXX	
32						XXXXXXXXXXXXXXXXX5	
28						XXXXXXXXXXXXXXXXXX	
24						XXXXXXXXXXXXXXXXXX	
20						2XXXXXXXXXXXXXXXXXX	
16						XXXXXXXXXXXXXXXXXX	
12						XXXXXXXXXXXXXXXXXX72	
8						XXXXXXXXXXXXXXXXXX	
4		25				7XXXXXXXXXXXXXXXXXX7	
						5	
CHANNELS	10	0	1	2	3	4	5
	1	12345678901234567890123456789012345678901234567890					
CONTENTS	100						
	10						
	1.	12					
LOW-EDGE	10						
	1.						

```
* ENTRIES =      2195      * ALL CHANNELS = 0.2195E+04      * UNDERFLOW = 0.00
* BIN WID = 0.2000E+01      * MEAN VALUE   = 0.4615E+02      * R . M . S = 0.10
```

done.

wwdriv: message: bye.

D Revision History

Version 1.5, June 1996

- Anomalous couplings.
- “CC11” diagrams.
- LEP2 standardized ARIADNE, JETSET and HERWIG interfaces.

Version 1.4, Fall 1995

- LEP2 workshop.

Version 1.3, April 1995

- Canonical cuts and input parameters.
- Fixed inconsistent phase conventions, which resulted in wrong angular distributions.

Version 1.2, July 1994

- Coulomb correction.
- Improved JETSET and HERWIG interfaces.

Version 1.1, February 1994

- Hadronization, JETSET and HERWIG interfaces.
- Minor bug fixes.

Version 1.0, 1993

First official release, submitted to the *Computer Physics Communication Library*.